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MODELLING THE HEAT TRANSFER AND STRUCTURAL BEHAVIOUR OF PLAIN AND FRP CONFINED RECTANGULAR COLUMNS IN FIRE

Ershad CHOWDHURY [1] Mark GREEN [1] Luke BISBY [2]
Noureddine BENICHOU [3] Venkatesh KODUR [4]

[1] Department of Civil Engineering, Queen's University, Kingston, ON, Canada
[2] Institute for Infrastructure and Environment, University of Edinburgh, Scotland, UK
[3] National Research Council, Ottawa, ON, Canada
[4] Civil and Environmental Engineering, Michigan State University, East Lansing, MI, USA

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1 INTRODUCTION

In recent years, existing concrete structures in North America have reached a state where many of them can no longer safely resist the loads acting on them due to electro-chemical corrosion and to increased load requirements, among other factors. Fibre-reinforced polymers (FRPs) have demonstrated good performance in retrofitting and repairing these deteriorated reinforced concrete structures, through both research studies and field applications. However, because of a lack of available information and the perceived susceptibility of these systems in fire, an experimental and analytical study is being conducted on the fire performance of FRPs and FRP-strengthened concrete structural members. The ultimate goal of the study is to provide design recommendations and guidelines that can be suggested for these types of structural members. This paper presents the procedure used in developing a model for the heat transfer and structural analysis of rectangular FRP-strengthened reinforced concrete columns in numerical fire simulation models. Preliminary results and partial validation of the analytical model are presented.

2 ANALYTICAL MODEL

A numerical model was developed and programmed in FORTRAN to predict the temperatures within a rectangular reinforced concrete member, and subsequently to predict the structural behaviour of FRP confined, square, reinforced concrete columns in fire. An explicit finite difference method is employed to predict the heat transfer within the column, since a similar technique was successfully used for modelling both conventional reinforced concrete structures [1-5] and FRP-strengthened reinforced concrete structures [6, 7] in fire. The structural behaviour in fire is determined using classical sectional analysis and the column deflection curve (CDC) method presented by Chen and Atsuta [8]. The structural model accounts for the non-linear thermal and mechanical response of all constituents, the confining effect of the FRP wraps, and the second-order moments in slender columns.

2.1 Heat Transfer Model

The cross-section is discretized into a user-defined number of rectangular elements, as shown in Fig. 1. In the numerical model, the temperatures to which the exterior of a member might be subjected in the event of a severe building fire are represented by a standard temperature-time curve according to ASTM E119 [9]. The heat transfer from the centreline of the column to its exterior surface is calculated using a series of two-dimensional explicit finite difference formulae based on an elemental energy balance. The formulation of the finite difference equations and the maximum allowable time step to ensure stability of the explicit finite difference algorithm are based on theory described by both Cengel [10] and Lie [2]. The variations of the thermal properties of the materials have been taken into account using relationships described by Lie [2] and Bisby [11]. Once the column temperatures at each element in the cross-section are calculated, the next time step is considered and the procedure is repeated. The temperature of the central node of each element is assumed to represent that of the entire element.

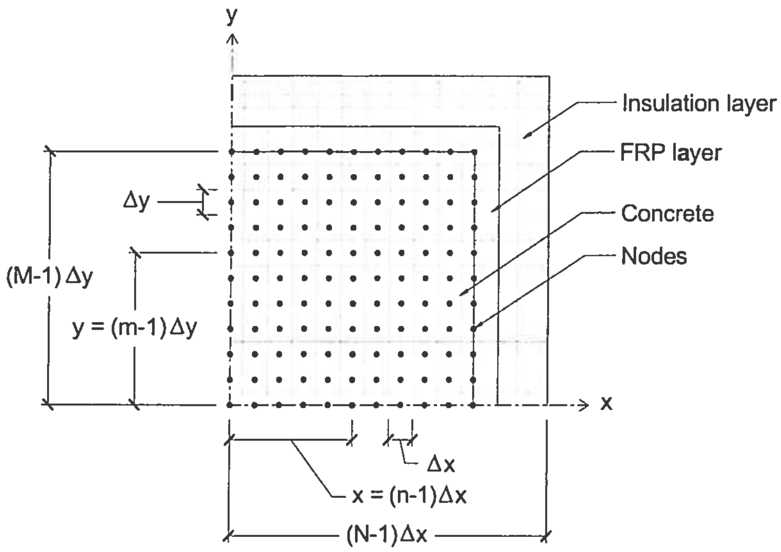

Fig. 1 Discretization of one-quarter cross-section of an insulated and FRP-strengthened rectangular column (nodes on the FRP and insulation layer not shown)

2.2 Structural Response Model

Once the temperature distribution of the column cross-section is determined at each time step, variations of the mechanical properties of the materials with temperature are determined. The compressive stress-strain model proposed by Lie [2] for unconfined concrete and the model proposed by Lam and Teng [12] for confined concrete are used (modified to account for high temperature deterioration of material properties) in the numerical analysis. The stress-strain model by Lie [2] for reinforcing steel and the stress-strain model proposed by Bisby [11] for FRP materials are also included in the numerical analysis. The temperature and strain in the longitudinal reinforcing steel is assumed to be the same as those for the concrete element at the location of the centroid of the steel bar. The mechanical properties of the FRP material are determined based on the highest temperature experienced by the elements within the FRP (refer to Figure 1).

The objective of the load capacity model is to determine the failure axial load for an eccentrically-loaded column at each time step, which requires the derivation of the moment versus curvature relationship for increasing load levels, followed by calculation of axial load-moment load paths for a given eccentricity. The method of analysis is based on the following standard assumptions: (1) plane sections remain plane after loading, (2) strain in the reinforcement is equal to the strain in the concrete at the same location, (3) the longitudinal stress at any point in the cross-section is dependent on the longitudinal strain, and (4) the tensile strength of the concrete is negligible.

Using an iterative procedure, the moment-curvature relationship for a given axial load is calculated. To derive the moment-curvature relation, various strain profiles are assumed across the cross-section by incrementally increasing the concrete strain at the extreme compression fibre up to the failure axial strain in the most compressed region. The structural model accounts for thermal strain and transient strain (which is a specific phenomenon for concrete under fire conditions) along with the instantaneous stress-related strain. For each proposed strain profile, an axial load and bending moment are calculated by performing a sectional analysis. The calculated axial load is compared to the given applied load, and the strain profile is modified and the procedure repeated until the calculated load is equal to the applied load within a specified tolerance. Once the moment-curvature relationship for a given axial load is determined, the slope and lateral deflection are calculated along the longitudinal height of the column using the CDC method described in Chen and Atsuta [8]. This numerical integration method accounts for the effect of secondary bending moments caused by the coupling of axial load and lateral deflection. Both material and stability (or buckling) failure modes are considered in the analysis. For each time step, an axial load versus moment path of the column is determined by increasing the applied load incrementally. Thus, from these axial load versus moment paths at various time steps, the load capacity with increasing temperature can be determined.

3 PRELIMINARY RESULTS

Preliminary results from the heat transfer and structural model for a square reinforced concrete column are shown in Fig. 2. Temperature variations at various locations within the reinforced concrete column and the load capacity with increasing temperatures have been validated using experimental data presented by Lie and Woollerton [13] on a 305 mm square, carbonate aggregate concrete column which was reported to have a relative humidity of 76% under ambient conditions prior to fire testing. The predictions from the current heat transfer model agreed well with the experimental results. As shown in Fig. 2, temperatures calculated along the line AC within the concrete were higher than along the line AB, as should be expected. The heat transfer model underestimated the temperatures near the core of the column cross-section because moisture migration within the elements was not included in the heat transfer analysis. In the numerical model, after the temperature of a concrete element reaches 100°C, the temperature remains at 100°C until all the moisture has evaporated, that is, all the heat supplied to the element is assumed to be used for the evaporation of moisture [4]. In reality some of the moisture moves towards cooler regions of the column resulting in higher temperatures in practice than predicted by the model.

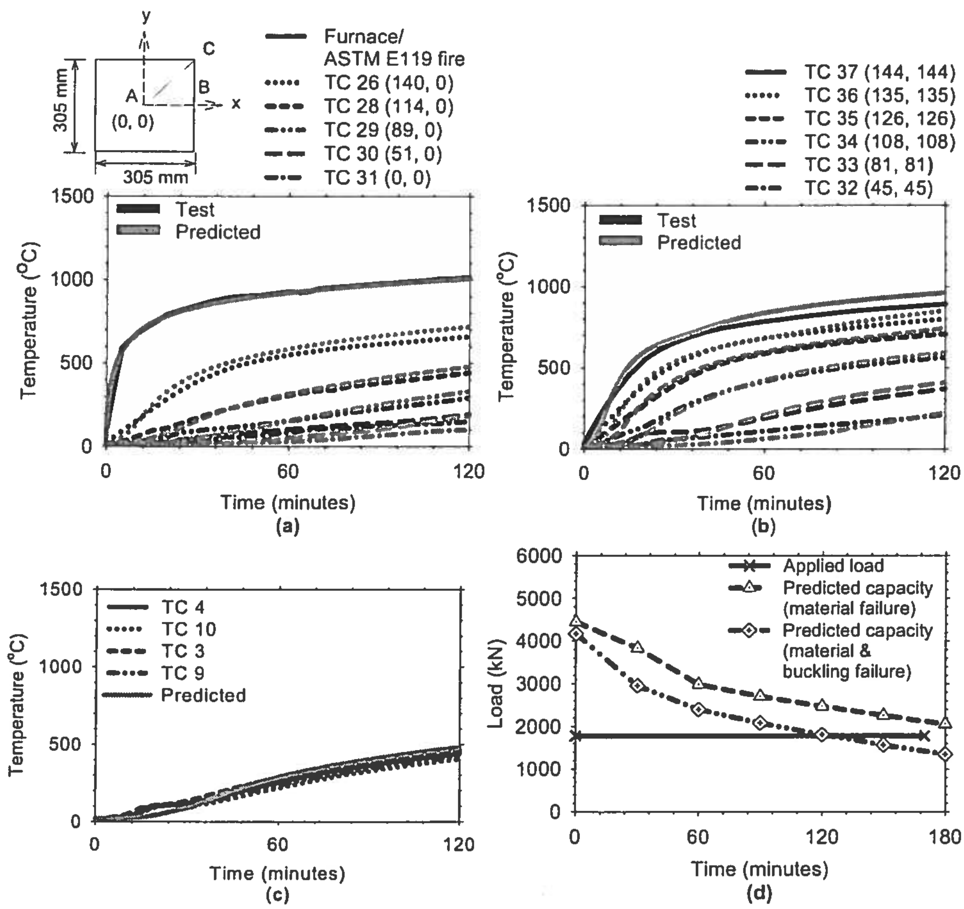

Fig. 2: Predictions from the heat transfer and structural model – (a) temperatures along the line AB, (b) temperatures along the line AC, (c) temperatures of reinforcing steel, and (d) failure load versus time.

Fig. 2(d) shows the predicted loss of strength for the square reinforced concrete column specimen with increasing temperature. The column was reinforced with four 25 mm diameter longitudinal steel bars with a clear cover of 48 mm. The yield and ultimate strength of the steel bars was 444 MPa and 730 MPa, respectively. The compressive strength of the concrete was 39.9 MPa. Though the column specimen was 3810 mm long, the column length during the structural analysis was taken to be 3000 mm, which was the length of the column exposed to the fire [4]. It is evident that the load capacity predictions of the model are conservative when both modes of failure (material and buckling) are considered. Based on the results from the numerical model, failure occurs after 120 minutes of fire exposure, whereas, during the fire test, failure occurred after 170 minutes. However, when only material (crushing) failure mode is considered, the numerical model overestimates the time of failure which indicates the need to consider the effects of slenderness in the structural analysis.

4 SUMMARY AND CONCLUSIONS

The discussion and results presented herein highlight a preliminary study on the development of a numerical model to predict the thermal and structural behaviour of FRP wrapped square reinforced concrete columns under exposure to a standard fire. The numerical model needs to be validated against experimental results of rectangular FRP strengthened concrete columns before it can be used with confidence. Nonetheless, the numerical model is able to make reasonable predictions of the internal temperatures within and the load capacity of, rectangular plain (without FRP) reinforced concrete columns in fire. The key aspects of the numerical model that must be modified and evaluated relate to moisture migration and the thermo-mechanical properties of the FRP and insulation materials. Therefore, further studies are currently underway on these materials at elevated temperatures.

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